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MASCONS AS STRUCTURAL RELIEF

ON A LUNAR MOHO

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ABSTRACT

A mechanism for the creation of lunar mascons is proposed that requires no abnormal density materials nor density inversions. The mascons are produced by mantle plugs upwelling into giant impact basins punched through the lunar crust followed by volcanic filling of the remainder of the crater above the plug. It is explicitly shown that continued volcanic filling is not inhibited by the attainment of isostatic equilibrium. This model predicts a minimum crustal depth of 45 km in the Imbrium region, assuming a 0.5 gm/cm^3 density contrast between the lunar crust and mantle. The strength of the lunar mantle must be somewhat greater than the Earth's, however, this is not inconsistent with a composition essentially similar to the Earth's. The approximately linear relationship between the peak gravity anomaly and the mare basin diameter suggests that for craters less than 200 km diameter, the strength of the moon is sufficient to prohibit the formation of a mascon by mantle upwelling and volcanic filling.

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INTRODUCTION

The discovery of large positive gravity anomalies by Muller and Sjogren (1968) associated with the giant circular basins of the moon has prompted numerous theories attempting to link the excess masses (mascons) with mechanisms for creation of the circular basins. These have included puddling of high density meteorite material (Urey, 1968), normal density basaltic lava filling a crater in a low density lunar crust (Conel and Holstrom, 1968) and anomalously high density lava filling a crater in a normal density lunar crust (Baldwin, 1968). The present paper utilizes a simpler model of a relatively normal density lunar crust and mantle, separated by some kind of a lunar Moho. The observed mascons are then produced by mantle plugs upwelling into giant impact basins punched through the lunar crust followed by volcanic filling of the remainder of the crater above the plug. The model is illustrated in Figure 1.

THE MODEL

Density of the lunar crust and mantle is assumed to follow the most common types of terrestrial basic rocks and to be similar to the Earth's oceanic crust and mantle at about 2.8 and 3.3 gm/cm^3, respectively. Following Baldwin's scaling arguments (1968) a basin the size of Imbrium is illustrated in Figure 1 having a depth of about 50 kilometers, although the mechanisms would work equally well with other crater depths. If the crater was entirely in "basaltic" lunar crustal material a stress difference of 3 kilobars would exist between the normal crust and the adjacent 50 kilometer deep hole, a stress difference quite adequate for appreciable solid flowage and isostatic upwelling of the deeper mantle material as a plug into the bottom of the hole. A theoretical limit to the isostatic upwelling is provided by the density ratio of 2.8/3.3 or 85% of the 50 km crater depth. It is unlikely that the upwelling mantle plug could reach its full structural relief because of decreasing stress differences as equilibrium is approached and because of volcanics being piled on top of the rising plug.

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A reasonable upper limit to plug height for the 50 km crater might be 2/3 its theoretical height of 42.5 km, or about 30 kms, a structural relief within the range required by the Imbrium gravity data.

Once isostatic equilibrium had been reached by some combination of plug rise and volcanic fill, the crater floor would still be 5-7 km below the lunar surface adjacent to the basin. Considering the tendency of even modest depth, young lunar craters like Tycho and Aristarchus to have apparent volcanic filling to about the same level as the adjacent maria, the much larger and deeper topographic basin above the plug should also be filled to approximately the same regional level of mare flooding, which on the near side of the moon is about 1 km below the level of adjacent highlands.

Depending on the strength of the moon and the excess mass of the buried plug, the weight of the final lava fill would eventually begin to force the plug back down again. As the plug subsided so would the overlying surface, permitting additional small increments of volcanic fill to raise the level back up to the general level of volcanic flooding. The result would be a long and complex history of volcanic flooding similar to that suggested by detailed lunar geologic mapping in the circular basins (Schmitt, et. al., 1967). Smaller craters in the region would be slowly tilted toward the subsiding plug to be differentially flooded on the plugward side, a long noted aspect of the circular basins.

Inward movement of deeper crust and mantle material toward the growing plug plus lack of lateral support in the crater walls produces the typical concentric collapse of adjacent highlands into the circular basins. The subsurface result of the collapse is a slightly depressed Moho moat surrounding the plug (Figure 1). This Moho moat coupled with topographic corrections for the surface collapse rings can account for the circle of negative gravity anomalies seeming to surround the positive mascons, as discussed in a following section.

The nature of the volcanic fill of the crater and of low areas in the adjacent collapse rings (Figure 1) is uncertain, but if the fill is assumed to be basaltic material similar in density to the adjacent lunar crust it would be indistinguishable gravimetrically from that crust. If so, only the buried plug and the surface topographic effects would contribute to the gravity anomaly. When first formed, the open crater would produce a negative gravity anomaly; when partially filled with plug and volcanic cover, the anomaly would become zero; when completely filled with the volcanics there would be excess plug mass and hence a positive gravity anomaly or mascon.

DATA FIT

The proposed model must be capable of fitting the presently available data. In that there can be no unique solution from gravity data alone, the best that the model can produce is a family of Moho plugs all of which fit the gravity profiles.

The Imbrium basin was selected for study because of Muller and Sjogren's (1969) detailed map of the area (Figure 2) plus sufficient topographic data to make possible an estimate of the amount of surface collapse around the central plug. This is taken to be 1 km and is reflected in the models as a cylindrical surface depression 1 km deep and 1200 km in diameter. The subsurface expression of this basin is represented as a Moho moat, a washer-shaped depression in the Moho surrounding the upwelled plug and of similar dimensions as the surface depression. Figure 3 shows the family of Moho plug geometries used to match the Imbrium gravity anomaly.

The comparison of the calculated gravity anomalies for these models and the Imbrium data is shown in Figure 4. The data points were taken along section A-B of Figure 2 and averaged on opposite sides of the center to produce a symmetric curve. The agreement between the models and the data is adequate considering the 20% uncertainty in the data due to the inherent ambiguity in measuring only line-of-sight accelerations of the spacecraft.

In fitting the models a number of requirements appeared. The plugs had to have dome shaped tops (approximated by a series of steps in the models); cylindrical plugs produce excessive widths of positive shoulders on the gravity curves. The topographic basin is required to produce the negative shoulders on the curve. The Moho moat contributes to this effect but is unable to produce the total negative anomaly without excessive structural relief on the Moho beyond that indicated by the magnitude of surface collapse.

An example of the sensitivity of the negative shoulders of the curve to the depth of the topographic basin is presented in Figure 5. The curve for the 120 km deep Moho from Figure 4 is reproduced along with the curve produced by changing the topographic basin depth from 1 km to 3/4 km. The fit is better, but it seems unrealistic in light of the present uncertainties of both the gravity profile and of the topography to try to determine lunar relief by this method of changing models.

Some of the pertinent characteristics for this family of Moho plugs of Figure 3 are presented in Table 1. The original Imbrium crater using Baldwin's 50 km depth had a mass of $\sim$ 350 μ moons (10^{-6} moon masses). The 1 km residual topographic basin would have a negative mass of $\sim$ 40 μ moons. The plug masses are about 300 μ moons whereas the excess mass creating the gravity anomaly is about 15 μ moons.

The density contrast of 0.5 was chosen as most probable using the typical terrestrial basic rocks. The plug heights and crustal thicknesses of Table 1 reflect that assumption. With other density contrasts, other families of plug height to crustal thickness ratios can be obtained as in Figure 6.

MECHANICS

The proposed mechanism for the creation of mascons relies on two independent processes: the upwelling of mantle material to achieve isostatic equilibrium, and then filling of the remaining depression with hydrostatically rising volcanics. This mechanism may be confused with a physically impossible one that requires liquid (magma) to flow uphill. This confusion stems from a sometimes forgotten basic difference between the two processes: isostasy is a static balancing of weights of crustal columns whereas volcanic activity can be a form of crustal foundering shifting lighter material to the surface and denser material downward, thus lowering the center of gravity of the column without affecting its total weight. This section attempts to clarify this confusion by describing these two processes in semi-quantitative detail.

On earth the mantle is the mother of basaltic magmas although the precise processes are not clear. It is still debatable whether the creation of a magma chamber at depth is the result of phase changes or filter pressing and whether the driving agents are local pressure drops associated with tectonic stresses, water distribution, and/or local heating. Once formed, however, the magma is a liquid of lower density than the surrounding mantle rocks and at least temporarily must support most of the weight of overlying rocks by a hydrostatic pressure approaching lithostatic pressure. A steel cased hole drilled into this magma chamber would have a column of the less dense (2.7) magma standing in it to a height such that its weight is equal to the weight of the column of rock above the chamber. For a hole drilled to 100 km through 50 km of crust of ρ = 2.8 and 50 km of mantle of ρ = 3.3, the magma column would have an equilibrium height 13 km above the topographic surface.

In the real situation the channel to the surface must be held open by the pressure of the lava combined with tectonic stresses. Thus depending on the nature of the tectonic stresses and the lithostatic pressure buildup in the magma chamber the actual magmatic column will be able to reach some fraction of its theoretical (hydrostatically balanced) height. It seems likely that this actual height to which magmas can rise will ultimately determine the level to which the surface topography can be built by volcanic means.

In effect this process would determine the general level of mare flooding on the moon. Because of the displacement of the lunar center of gravity from the center of volume, this level of volcanic flooding is essentially at the topographic surface on the near side but substantially below the topographic surface on the far side of the moon (Masursky, 1969).

The principles involved in the contrast of isostatic loading versus volcanic flooding are illustrated in Figure 7A wherein the hydrostatic pressure of 2.7 density lava column is shown by curve SA and lithostatic pressure in a two layer crust of ρ = 2.8 and 3.3 is shown in curve SB. A closed magma chamber would have to withstand the lithostatic pressure and hence for a given depth X the magmatic pressure would have a value approximating B rather than A. A cased well drilled to the chamber at depth X would have an equilibrium magmatic (hydrostatic) pressure gradient BC and hence could have magma standing at a height SC above the surface. The practical requirements of moving the magma upward, limit the height of the column to S, the average level of regional volcanic flooding. A crater blasted to the Moho (Figure 7B) would have a crustal loading directly beneath it of curve MQ. Isostatic rise of a plug of height PM with a cap of volcanics of thickness VP would eventually shift the MQ curve to the lithostatic pressure curve VRB, as the area was brought back to isostatic equilibrium. Part of the original crater SV still remains open but as far as the deep crust is concerned the superficial loading is the same, and hence magmas can still rise to the same theoretical height (C) or practical height (S). The result (Figure 7C) will be filling of the still open portion of the crater with volcanics, raising the curve VRB to become curve SUZ (Figure 7C). The greater crustal load of SUZ over the original VRB is the magnitude of departure from isostatic balance or the excess mass now seen as the mascon gravity anomaly.

As a way of quantifying the details of the volcanic extrusion process, a fictitious circular portion of the lunar surface of 1200 km diameter and 100 km depth is assumed (Figure 8A). The upper half is an impermeable crust of ρ = 2.8 and the lower half is a hypothetical sponge of material of ρ = 3.9 with 50% porosity and all pores filled with magma of ρ = 2.7, resulting in an average "mantle" density of 3.3. The "mantle" supports the overlying "crust" by the pressure on the pore fluid being equal to the lithostatic pressure of the overlying load. A cased hole drilled to the bottom of the section would have magma of ρ = 2.7 standing in it to an elevation of 13 km above the surface.

A 600 km diameter crater is impacted into the center of this area (Figure 8B), excavating a cylindrical crater precisely to the "Moho" and spreading half the crater mass as a uniform 8.3 km thick blanket (of density 2.8 for simplicity) over the surrounding area. The other half of the throwout debris is assumed to be thrown beyond the area of interest. We now have a negative gravity anomaly over the crater.

The crater is brought back to isostatic equilibrium by the rise of a 27 km plug of mantle capped by 25.5 km of volcanics of ρ = 2.8 (Figure 8C). The crater and adjacent crust are now in isostatic balance but the crater is still 5.5 km deep. The loss of magma from the "mantle" has raised its average density to 3.37. A cased hole from the bottom of the section would now have magma standing in it 11 km above the surface of the debris blanket. Volcanics would be about as capable of reaching that surface elevation as the pre-crater volcanics were of reaching the earlier surface with a "magma" head of 13 km. Once the final filling with 2.8 volcanics to the general surface level had been accomplished (Figure 8D), the fill would disappear gravimetrically and the residual positive anomalies in the gravity picture would be due to the "Moho" plug plus any topographic effects.

The center of gravity of the original model is 48.0 km above the base; with the fresh crater blasted out it is 47.9 km; with the plug alone it is 45.9 km; with the plug plus enough volcanic fill to bring it to isostatic equilibrium it is 44.8 km; with final volcanic filling beyond isostatic equilibrium to produce the positive anomaly, the center of gravity drops to 44.6 km above the base. The steadily falling center of gravity provides the energy for the magmatic movement.

In this schematic model no material is allowed to enter the cylindrical region from the outside. This results in the surface being 6.6 km below its original level by the end of the process. In the real situation, of course, lateral flow of material does occur maintaining the surface closer to its original level and contributing additional mass to the region.

DISCUSSION AND CONCLUSIONS

Some additional constraints exist on the models used to match the Imbrium gravity data. If it is assumed that volcanic cover and decreasing stress differences preclude a plug from reaching more than 2/3 of its theoretical height (85% of crater depth with the assumed densities) then the depth to the lunar Moho of the shallowest model with a 26 km plug would be 45 km. Accordingly if (a) the model is correct, (b) the densities are correct in being similar to earth's oceanic crust and mantle and (c) the orbital gravimetric data is correct, then a minimum depth to the lunar Moho is 45 km in Mare Imbrium.

The mascons represent crustal loading which must be supported by the strength of the lunar interior. The differential stress between the center of the several plugs and the normal crustal column at the depth of the adjacent Moho is given in Table 1. Realistic values of the maximum shear stresses when spread out over a greater area at depth may be only 1/5 to 1/3 these values or 50-100 bars (Conel and Holstrom, 1968). Nevertheless they are up to half an order of magnitude greater than the long term strength of the earth's crust. We do not conclude that this necessitates a radically different lunar interior than the earth's. The lack of a convecting interior, or of pressure/temperature values adequate to produce a weaker low velocity zone in the moon's crust could contribute to the greater lunar strength. A lower thermal gradient than the earth, reflecting lower ratio of mass to surface area could mean increased strength but poses difficulties with the depth required for the seemingly abundant volcanic activity recorded on the moon. Among the explanations of greater strength might be a much lower water content in the lunar mantle than in the earth's, in that the presence of water markedly decreases the strength of magnesian silicate rocks (Riecker and Rooney, 1966).

A plot of the magnitude of the mascons versus the diameter of the associated circular basins (Figure 9) suggests a linear relationship, which under the proposed model would be an indication of plug height. The plot thus suggests that for a crater diameter of about 200 km or less significant upwarping of the Moho into the crater floors does not occur. Using the model this geometric limit would be a function of both the depth to lunar Moho and the strength of the lunar crust and interior.

In summary, we see in the Moho plug theory for lunar mascons a way of avoiding the anomalous density materials and density inversions of other hypotheses. Little more is required than an earth-like mantle giving rise to a somewhat basaltic crust, capable of using normal isostatic and volcanic processes to heal impact craters punched through it. We recognize the requirement of a stronger lunar interior posed by the mascons but not necessarily an interior radically different in composition than the earth's mantle. In short we do not believe that the Moho plug model is the only explanation of mascons, but with presently available data, this model has Ockham's razor to recommend it.

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Attachments
References
Table 1
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TABLE 1

MODEL	ANOMALOUS MASS PLUG-BASIN	PRESSURE AT BASE OF PLUG	CRUST THICKNESS	-	DEPTH TO PLUG	=	PLUG HEIGHT
A	9 μMOONS	166 BARS	27 KMS		1		26
B	10	195	61		30		31
C	7	318	125		80		45
D	22	380	172		120		52

MASS OF TOPOGRAPHIC BASIN = -42 μ MOONS

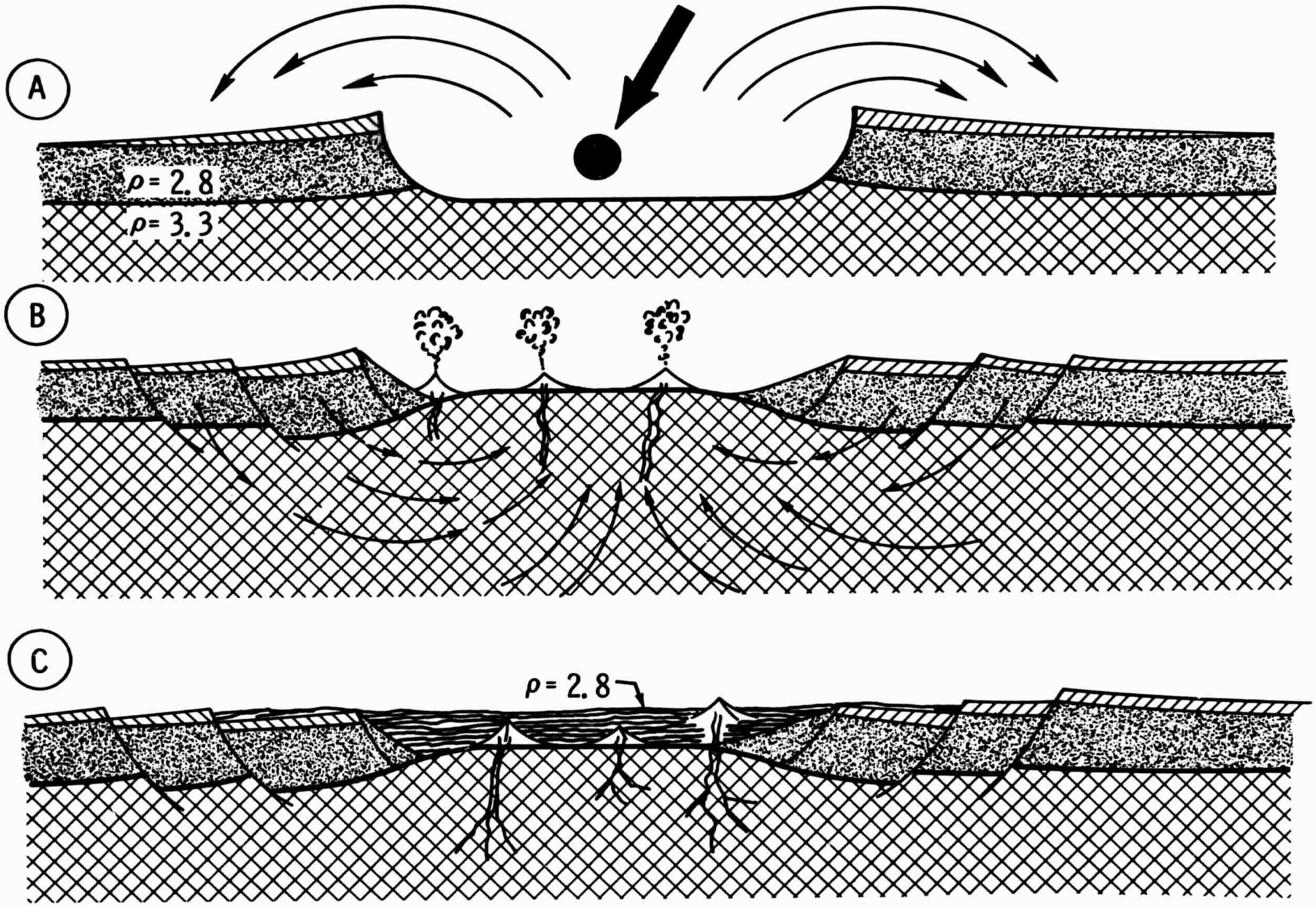

FIGURE 1 - FORMATION OF A MASCON

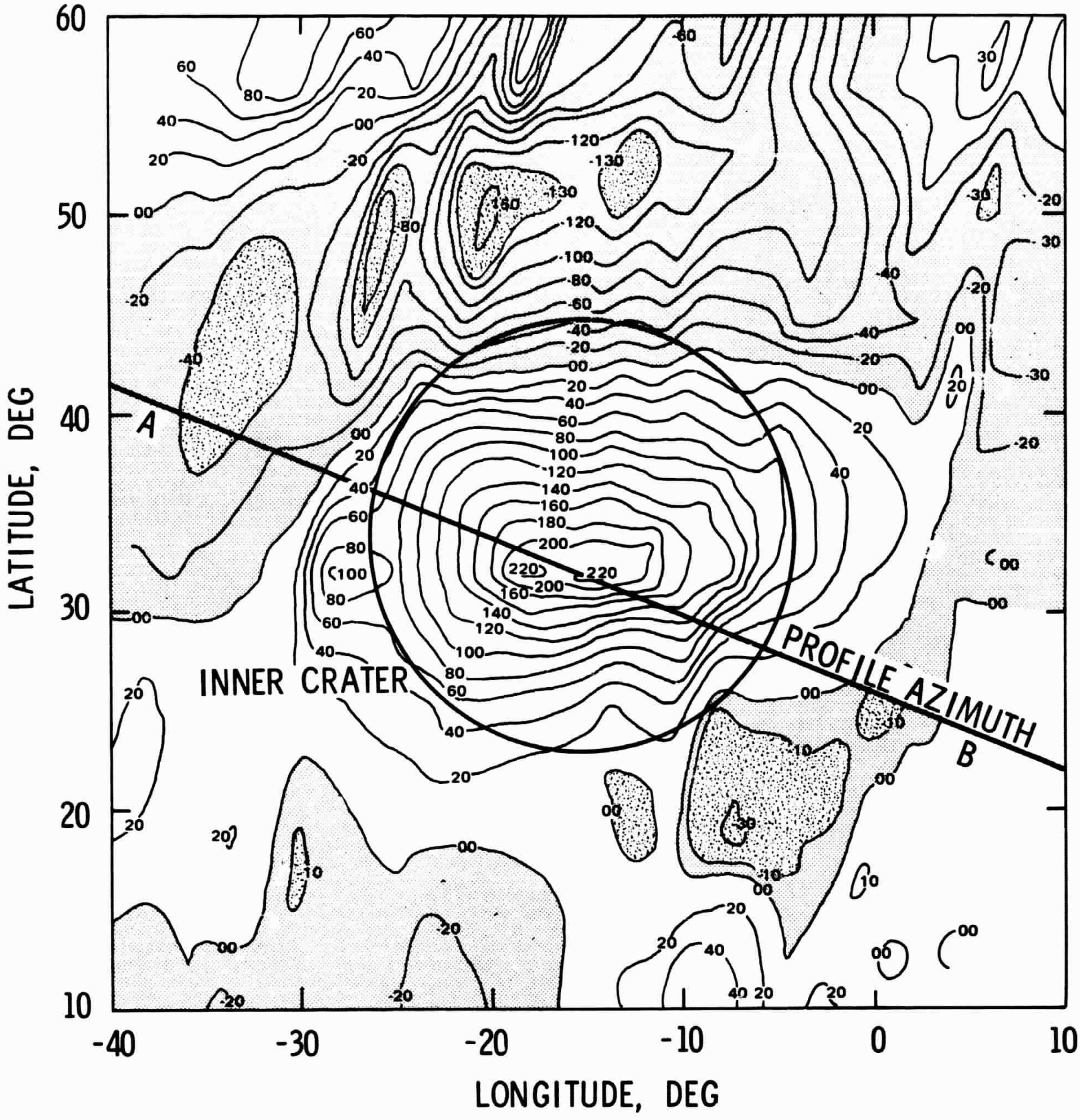

FIGURE 2 - DETAILED GRAVIMETRIC MAP OF THE IMBRIUM REGION FROM MULLER AND SJOGREN (1969)

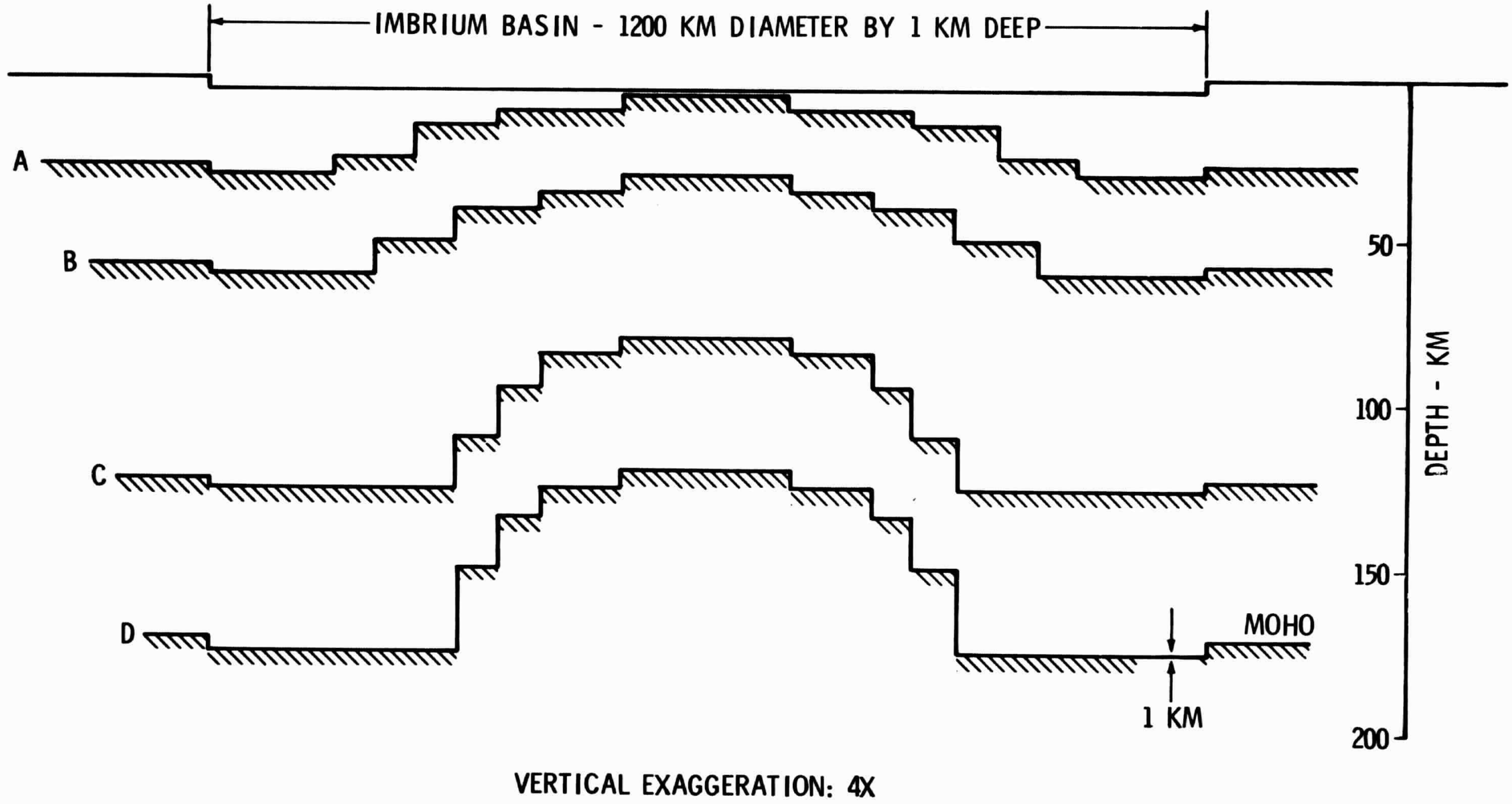

FIGURE 3 - MOHO PLUG GEOMETRIES USED TO REPRESENT THE IMBRIUM MASCON

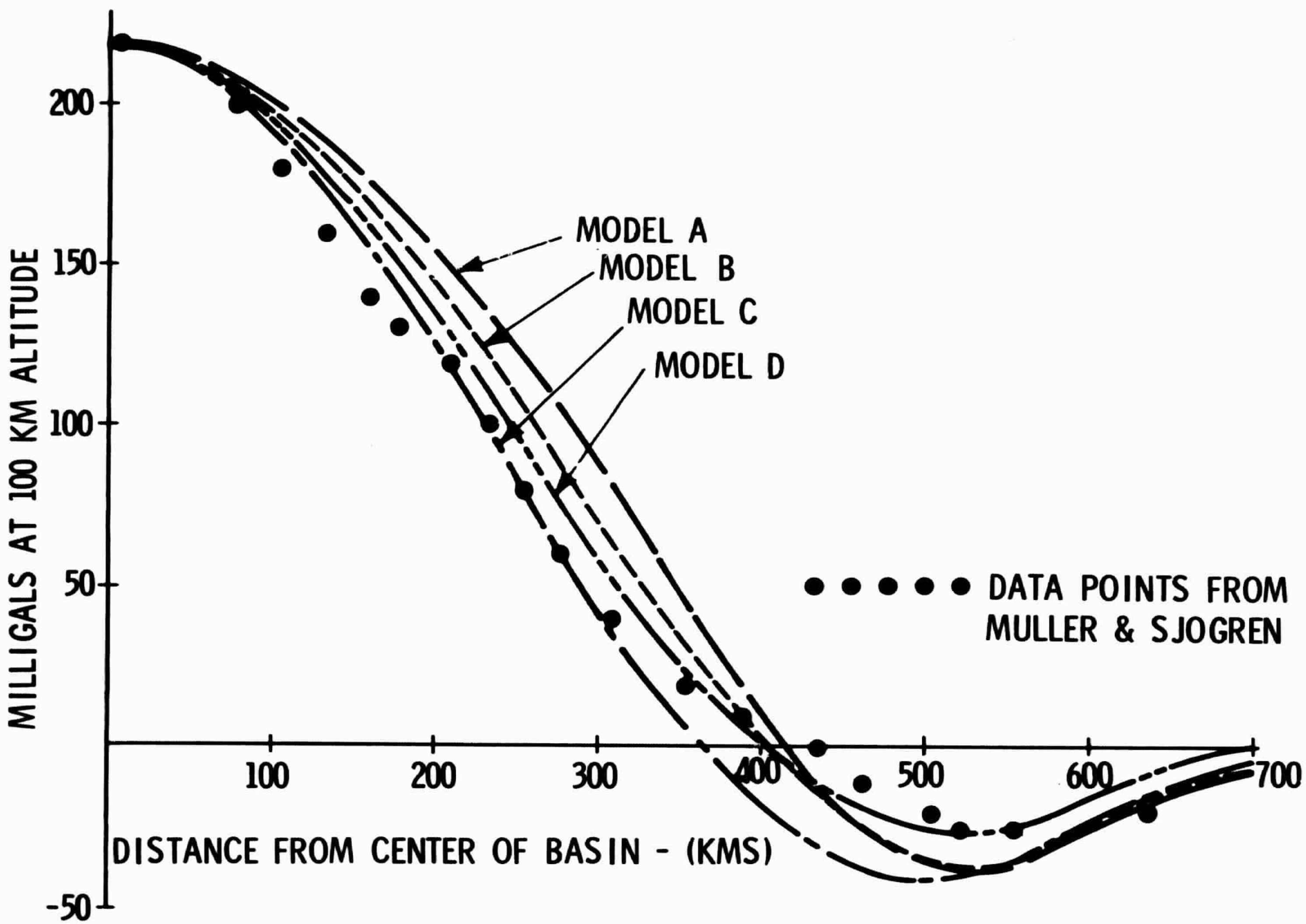

FIGURE 4 - CALCULATED GRAVITY ANOMALIES FOR MODELS COMPARED WITH IMBRIUM DATA

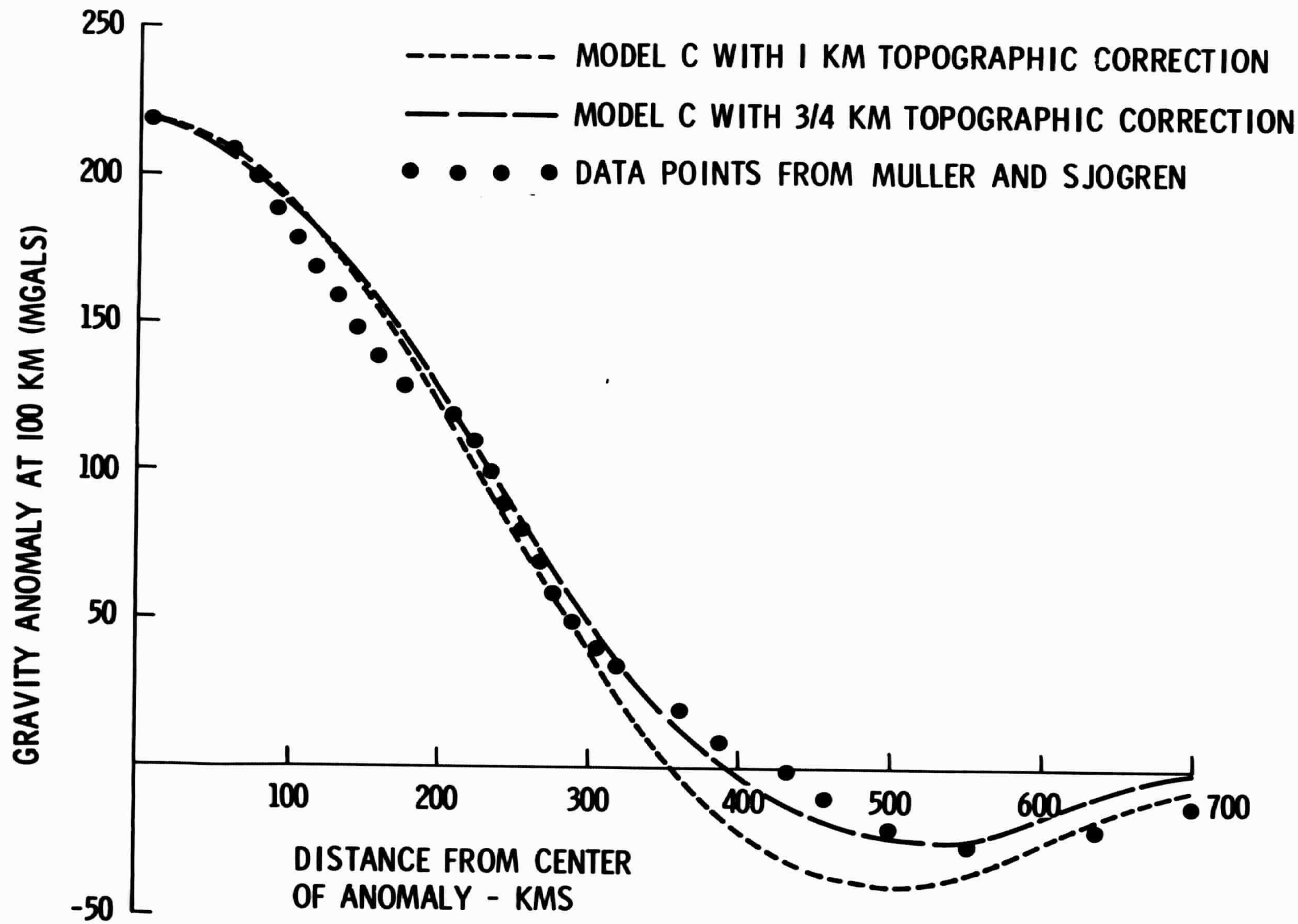

FIGURE 5 - SENSITIVITY OF NEGATIVE PORTION OF ANOMALY TO TOPOGRAPHIC CORRECTION

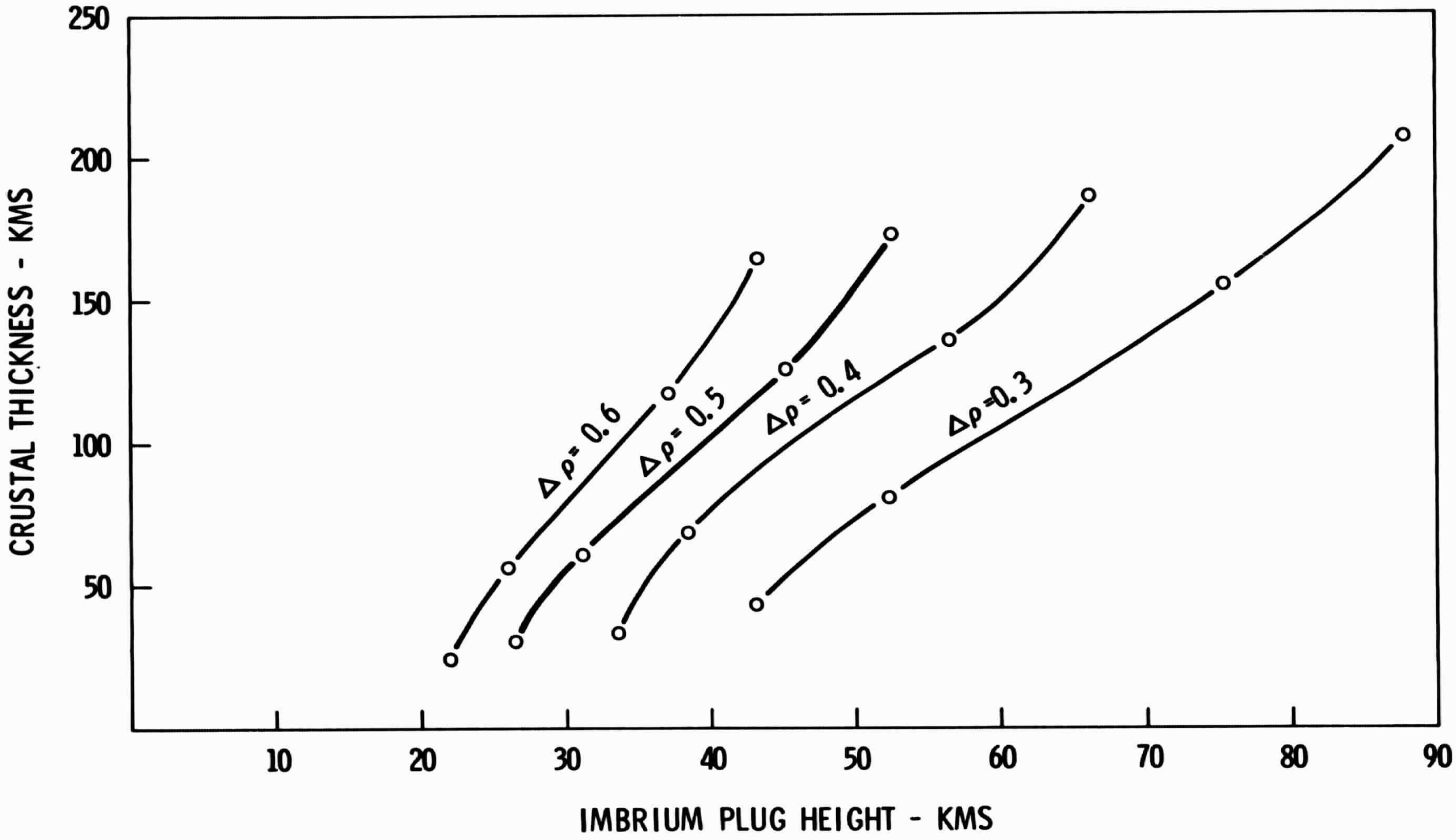

FIGURE 6 - DEPENDENCE OF MODEL DIMENSIONS ON ASSUMED DENSITY CONTRAST

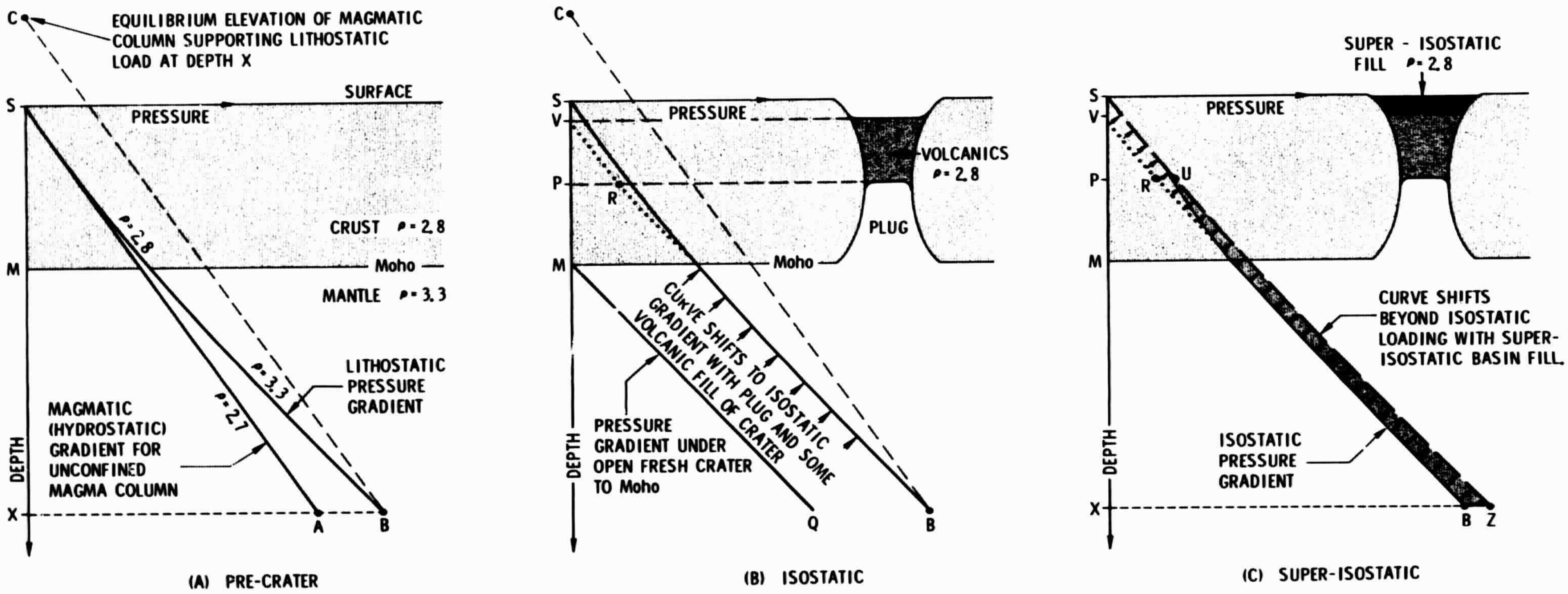

FIGURE 7 - PRESSURE REGIMES DURING THE FORMATION OF A MASCON

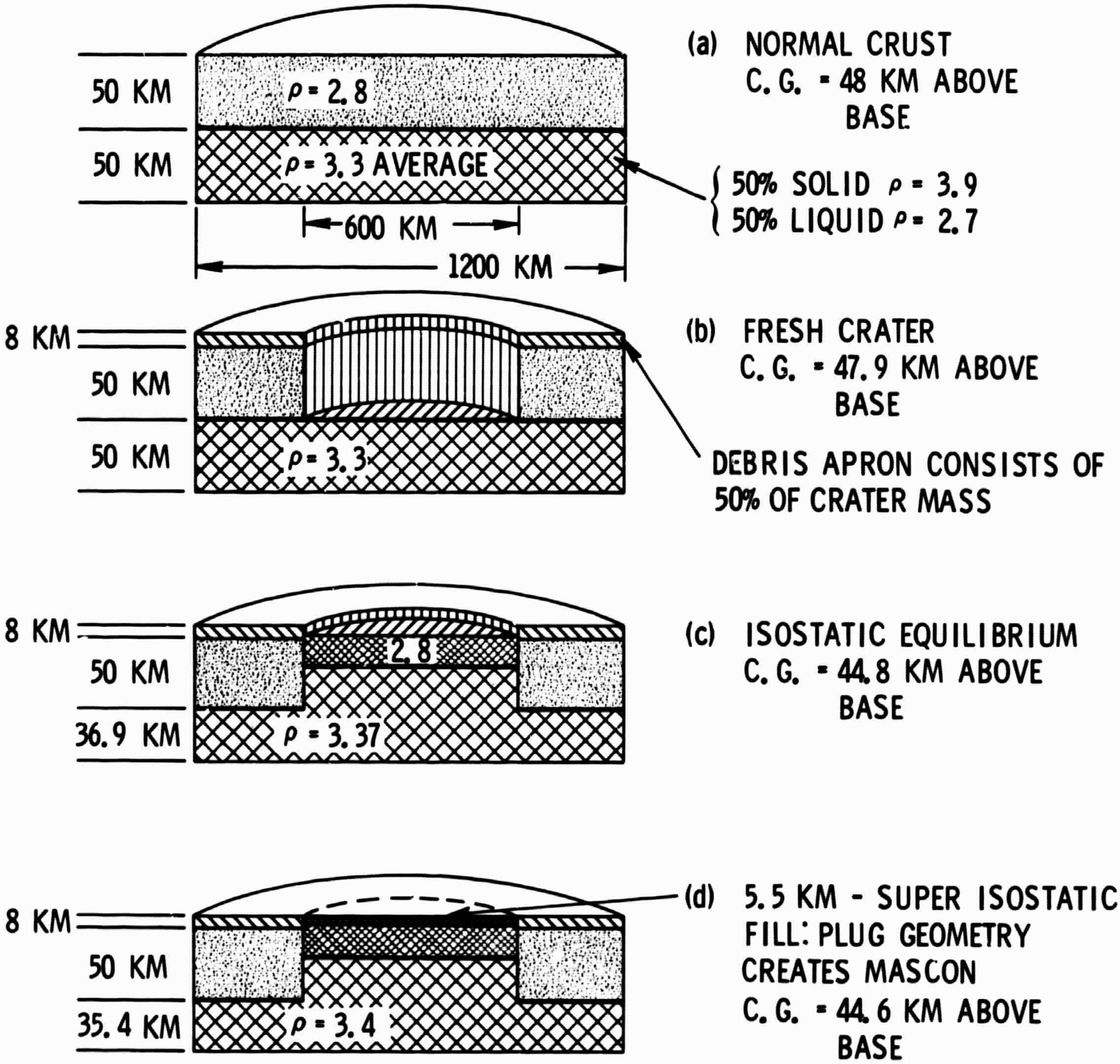

FIGURE 8 - SCHEMATIC REPRESENTATION OF THE STAGES OF MASCON FORMATION SHOWING THE FALLING CENTER OF GRAVITY

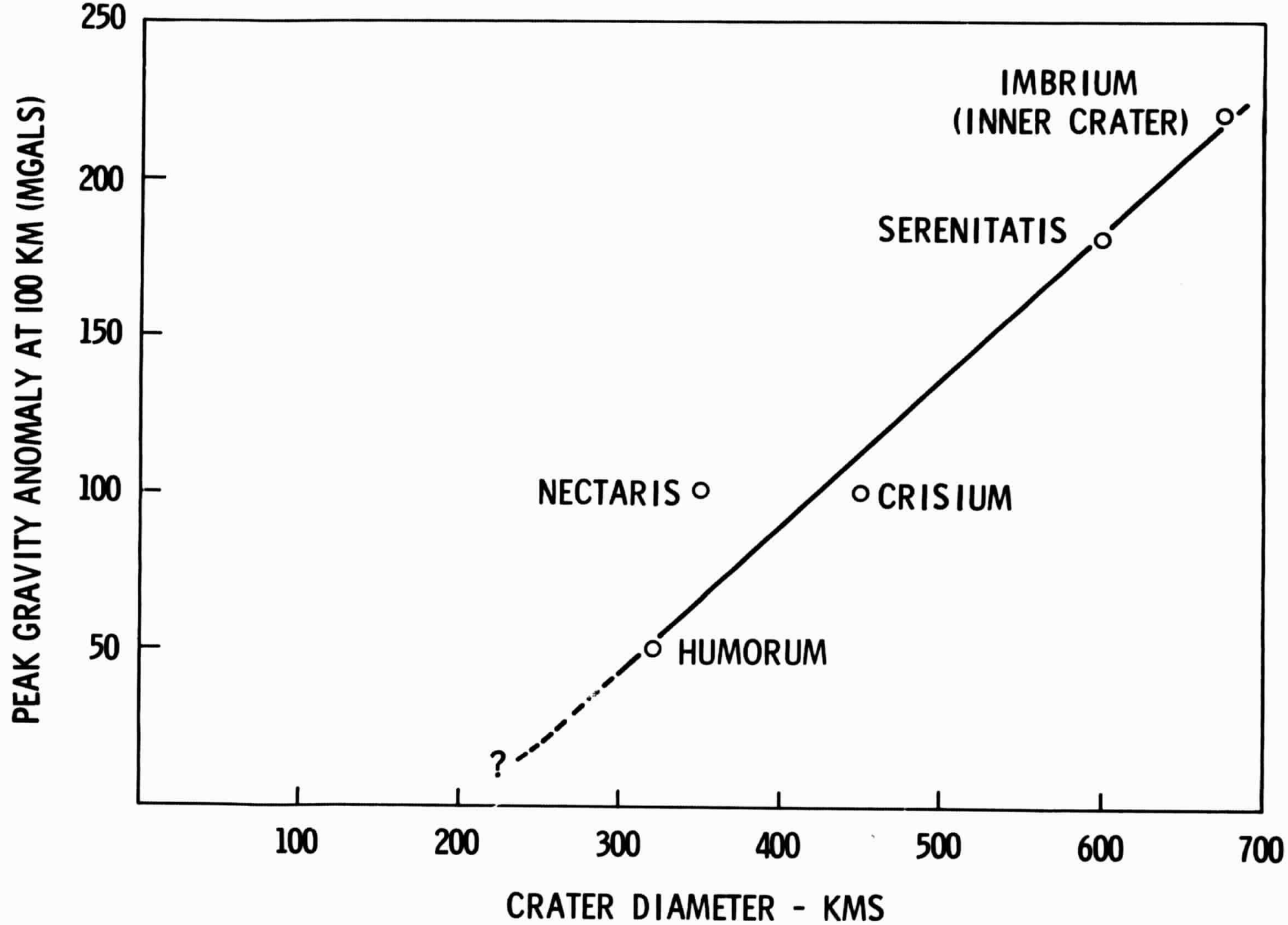

FIGURE 9 - PEAK GRAVITY ANOMALY VERSUS CRATER DIAMETER